Solar Radiation Estimation and Site Selection of PV Plant for Design of Hybrid System

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1. Introduction

Energy is the driving force of economic and social development. Rural development of any nation also related to access to the electricity. The fossil fuels such as oil, coal and natural gas are the main sources of energy for electricity generation. Therefore, these sources are backbone for growth of any nation. Due to the use of these conventional energy sources power generation in rural areas is very expensive due to remoteness and other physical barriers. The continuous use of fossil fuels for electricity generation leads to adverse environmental effect and rapid depletion of these sources (Verma & Kumar 2013). The remote sites are generally rich in renewable energy resources such as solar, hydro, wind, biomass etc. Availability of these resources depend upon the geographical conditions of the areas. However, these resources are variable intermittent and no-disperse. Therefore, combination of two or more than two renewable energy resources known as hybrid renewable energy system (HRES) (Krishna & Kumar 2015) are preferred for rural electrification where grid extension is not possible or very costly.

Moreover, the extension of grid-based electricity infrastructure into remote, mountainous, or sparsely populated areas often proves economically unfeasible and technically complex. The high capital cost of transmission lines, coupled with physical barriers such as rugged terrain, forests, or dispersed settlements, makes centralized power supply to such areas unsustainable. This creates a compelling need for decentralized, location-specific, and environmentally benign energy solutions that can operate independently of the national grid.

Fortunately, many rural and remote areas are naturally endowed with renewable energy resources such as solar irradiance, small streams and rivers, biomass from agricultural residues, and wind currents. These resources, when tapped appropriately, can provide clean, cost-effective, and reliable energy to underserved populations. However, the inherent variability, intermittency, and spatial dispersion of individual renewable sources limit their standalone utility. For instance, solar energy is affected by weather conditions and seasonal changes, while micro-hydro depends on stream flow, which can vary dramatically across seasons.

Designing and optimizing HRES for rural electrification is a complex and multidisciplinary task. It involves resource assessment, load demand estimation, system configuration, component sizing, cost optimization, and reliability analysis. Among the most critical steps is the accurate assessment of available renewable energy resources at the proposed site. For example, solar PV

sizing requires detailed information on solar radiation intensity, duration, and variability, while micro-hydro systems need data on water flow rates, head, and seasonal fluctuations.

In recent years, Geographic Information Systems (GIS) have emerged as powerful tools for spatial analysis, resource mapping, and site selection. GIS enables the integration and analysis of multiple layers of geospatial data, such as topography, land use, water bodies, solar insolation, population density, and infrastructure proximity. With the aid of remote sensing data and digital elevation models (DEMs), GIS can effectively estimate hydro potential and solar exposure across vast and inaccessible terrains. Furthermore, GIS allows planners to identify optimal locations for solar and micro-hydro installations based on resource availability, land suitability, and accessibility.

However, a major bottleneck in resource assessment is the scarcity of reliable and high-resolution data. Solar radiation data is often sparse and collected at a limited number of meteorological stations due to the high cost of pyranometers and data logging equipment. Similarly, hydro potential data, such as stream flow and discharge levels, may not be available for smaller tributaries in remote or mountainous areas. This data limitation hampers the precise design and feasibility assessment of HRES in such regions.

Artificial Intelligence (AI) methods, including machine learning, neural networks, and evolutionary algorithms, have demonstrated great promise in enhancing the precision and effectiveness of HRES modeling and optimization, and they can be used in conjunction with GIS. AI can be used to estimate energy demand, improve component sizing, assess system efficiency under various operating conditions, and close gaps in resource data. For example, AI models can forecast future streamflow patterns based on existing hydrological data or estimate missing solar radiation statistics using temperature, humidity, and cloud cover information. Artificial Neural Networks (ANN), Particle Swarm Optimization (PSO), and Genetic Algorithms (GA) are AI-driven optimization techniques that aid in system design by determining the most dependable and economical HRES designs.

Many studies have been conducted for the sizing of hybrid renewable energy system sizing for rural area electrification purposes. The sizing of these HRES requires resource assessment and specific site selection. For example, Solar PV plant sizing requires information of solar radiation

data and hydro plant require flow data for HRES sizing in specific location. Unfortunately, the solar radiation data at specific regions are very sparse and measured at very few locations due to very high cost of radiation measuring instruments. Therefore, this research focuses on HRES sizing incorporating resource assessment (solar +micro hydro) and site selection using GIS and AI techniques.

2. Brief Literature Review

2.1. Solar Radiation Assessment

Solar radiation measurements with calibrated Pyranometer's are available at select places only as they are expensive and require maintenance. Therefore, it is essential to estimate solar radiation using most accessible meteorological like relative humidity, temperature, sunshine hours as these are available at a large no. of locations. For estimation of solar radiations, many conventional models are found in literature (Gurel et al. 2023; Hissou et al. 2023). Some authors have used sunshine duration parameter to estimate monthly average solar radiation estimation (Kumar et al. 2015; Tadros 2000; Li et al. 2011; Alam et al. 2009). A correlation between the clearness index and air temperature was first proposed by (Prescott 1940). However, these conventional models are not very accurate and are unable to handle a large number of parameters due to complexity and nonlinearity of data (Mellit & Kalogirou 2008; Notton et al. 2013). In recent times, Artificial Neural Network (ANN) based methods have been garnering attention for developing estimation models. ANN is a computationally efficient technique for estimating solar radiations because it can deal with large, complex and nonlinear problems more easily (Mellit & Kalogirou 2008). Many researchers have estimated the solar radiation using artificial neural network (ANN) (Tandon et al. 2025; Rumbayan et al. 2012; Benghanem et al. 2009; Kumar & Kaur 2016) . Kumar et al. (2015) reported that the performance of ANN models is better than that of conventional models for solar radiation estimation. Çelik et al. (2015) have used latitude, longitude, month, monthly mean temperature and monthly mean sunshine duration to estimate the monthly solar radiation in Eastern Mediterranean Region of turkey. To find the best estimation accuracy of the different model different learning algorithms (LM and SCG learning algorithms), different input combinations and several numbers of neurons in hidden layer were used. The best in terms of accuracy was found to be MAPE= 2.802% and R^2=0.990%. Yadav & Chandel (2014) reported the need of selection of most appropriate input parameters to estimate solar radiation and

omit the non-relevant parameters. Yadav et al. (2014) have used Waikato Environment for Knowledge Analysis (WEKA) software and ANN to select the most important parameters for solar potential estimation. The input parameters found to be effective were temperature, maximum temperature, minimum temperature, sunshine hours, altitude, longitude, latitude. Authors reported that temperature, minimum temperature, maximum temperature, altitude were most important input parameters. Further, the study is replicated by taking two additional parameters i.e. extraterrestrial radiation and clearness index. The Rapid Miner software was used to rank the input parameters for solar radiations prediction. The results showed that extraterrestrial radiation and longitude have the lowest rank. The parameters temperature, latitude and sunshine duration were found to be the most influencing ones. Five different ANN models have been explored and it was found that the ANN-4 model with input parameters temperature, minimum temperature, maximum temperature, humidity and sunshine hours has the best performance with a minimum MAPE value 6.89%. Yacef et al. (2012) also used automatic relevance determination to find most suitable parameters for estimation solar radiation in Al-Madinah, Saudi Arabia. Based on automatic relevance determination method Sunshine duration and air temperature were obtained the most relevant input parameters for neural network using automatic relevance determination method. Many authors tried different combination of input parameters to choose appropriate input parameters on the trial and error basis (Zaim et al. 2023; Alam et al. 2009; Fadare 2009; Kumar & Kaur 2016). However, since solar radiation estimation is site specific. There is need to estimate them for given site with better estimation accuracy.

2.2. Site Selection of Solar Plant

Improper site selection adversely affects various aspects such as on plant capacity, power quality, efficiency, cost of electricity and environment. Therefore, prior to installation of PV power plants appropriate site selection has become critical issues (Uyan, 2015).Various authors have conducted the prefeasibility analysis of site selection for solar plant by considering economic, environmental, social, and political factors. Charabi & Gastli (2011) used multi criteria evaluation Fuzzy Logic Ordered Weight Averaging (FLOWA module) with GIS to assess the land suitability for solar farms in Oman. The presented study considered Technical, economic and environmental aspects to choose the land suitability. Chen et al. (2014) have used a hybrid MCDM based on GIS considering four dimensions namely environment, location, orography and climatology. Same

dimension were used by Carrion et al. (2008) to select optimal sites for grid-connected photovoltaic power plants. Tahri et al. (2015) has used AHP and GIS by considering four factors climate, location, orography and land use to calculate the corresponding criteria weight to find energy technologies in Morocco. (Xiao et al. 2013) have developed a model for desert photovoltaic power plants in northwestern China using analytic hierarchy process and GIS. Khan & Rathi (2014) have also made a study for site selection of solar plant using GIS in Rajasthan state of India. Few studies have been conducted on site selection of solar plant site selection in India (Khan & Rathi 2014; Sindhu et al. 2017), however, hilly region especially in Western Himalayan is unexplored.

2.3.Sizing of the Hybrid Renewable Energy System

Initially, the research on aspects related on Hybrid Renewable Energy System (HRES) was focused for increase the reliability and stability of grid. Thereafter, the need of Hybrid RES was incorporated to both grid and standalone system for rural electrification purpose. Various combinations of HRES such as solar- wind, solar- hydro, hydro- wind, hydro- solar-wind-batteries etc. were used for rural as electrification (Maheri 2014; González et al. 2015; Kenfack et al. 2009; Vineetha et al. 2016; Li & Qiu 2015; Mostofi & Shayeghi 2012; Upadhyay & Sharma 2016; Phurailatpam et al. 2018). Various optimization methods such as graphical construction methods (Markvart 1996), probabilistic methods (Vos et al. 2013) iterative methods (Kaldellis et al. 2012; Xu et al. 2013), artificial intelligence (Hakimi & Moghaddas-Tafreshi 2009; Rahi et al. 2012; Nafeh 2011) and hybrid methods (Nasiraghdam & Jadid 2012; Katsigiannis et al. 2012) have been proposed by researchers. Few studies have been conducted for optimizing the size of solar and hydro HRES using AI techniques. The probabilistic approach to find various combination of renewable energy system based on loss of power supply probability (LPSP). In probabilistic approach very few variables have been considered for optimization of the system size. The main disadvantage of this approach is that it cannot show the dynamic performance of energy system. Graphical method has also been used for the HRES sizing (Markvart 1996; Salameh 1994). In these studies, two variables are selected PV-wind and PV- Batteries. Parameters like solar PV module angle, wind turbine cost and height were not considered. Kaldellis et al. (2006) proposed a hybrid renewable energy model consisting of wind- diesel configuration by using iterative method. Xu et al. (2013) recommended a hybrid PV-wind – Batteries energy system for

minimizing the cost of the system. The authors also developed an algorithm using iterative process for both grid and off grid mode. The use of iterative methods for sizing of hybrid renewable system has computational problems (Upadhyay & Sharma 2014). Many artificial intelligent techniques such as artificial neural networks (ANN), genetic algorithms (GA), and Fuzzy logic are utilized by researchers to optimize a hybrid renewable energy system (HRES) in order to minimize the cost of energy (Zhou et al. 2010; Mahesh & Sandhu 2017; Kumar et al. 2013; Koutroulis et al. 2006). Koutroulis & Kolokotsa (2006) has developed an optimized sizing for hybrid PV-wind system by minimizing the cost of energy. The GA was used to find optimal configuration of hybrid as well as solely use of each energy system. Upadhyay & Sharma (2015) have proposed a HRES (solar, hydro, biomass and biogas) model by using PSO to cater the load of Dhauladevi block of Almora district in Uttarakhand, India. Akella et al. (2009) have proposed integrated renewable energy system (IRES) for Jaunpur block of Uttarakhand State, India. Pradeep and Tiwari (2011) has used HOMER software for sizing of hybrid energy system in rural area of Rajasthan. The application of AI in HRES designing problem is complex compared to others methods but can provide best sizing optimization by considering many variables simultaneously. Kaur et al. (2018) have made a techno-economic analysis of wind-photovoltaic (PV) based DC micro grid for supplying power to telecommunication towers in remote/rural areas to reduce carbon mission caused by diesel generator. Ali and Mohammed 2024 address the serious issues of sizing of HRES over their lifespan while accounting for uncertainties in energy sources and load demands.

3. Research Gaps

Based on literature reviewed, a number of research gaps, have been identified, these are enumerated below:

(i) AI-based models have been successfully developed to model solar radiation wind speed, mean temperature, relative humidity, insolation and cleanness index (in different scale, i.e. monthly, daily, hourly, etc.), thus improving the existing statistical approaches. These have been used for estimating data in sites where measurement instruments are not available.

(ii) AI-based models to estimate global solar radiation (GSR) using various parameters in different scale, i.e. monthly, and daily basis for a specific site are little explored and

literature is silent to compare the accuracy in different time scale for solar radiation estimation.

(iii) To estimate locally available micro hydro resource in rural and hilly region need to explore. Literatures available are very less on micro hydro.

(iv) Selection of most important meteorological parameters as input to AI based model need to explore and very less literatures available on selection of appropriate parameters for solar radiation estimation using ANN.

(v) The solar and hybrid system sizing based studies for rural hilly region in Indian context are very less.

(vi) To implement RE technologies and their site selection.

4. Problem Formulation

As per the interference drawn from literature the problem formulation of present study is to estimate solar radiation and site selection of PV plant for design of hybrid system.

5. Objectives of the Research

The main aim of this research is to assess renewable energy resources potential and techno economic analysis for resource allocation for rural electrification, a case study a part of state of Himachal Pradesh shall be undertaken with following research objective:

1. Forecasting of solar potential using Machine learning Techniques.
2. Find more appropriate parameters for solar radiation estimation.
3. Site selection of solar plant considering environmental and economic aspects.
4. Design of solar hybrid system.

6. Proposed Methodology

The methodology framed to fulfill these research objectives includes several processing steps, namely, Resource assessment, Prioritization of most suitable parameter responsible for solar radiation estimation, site selection of solar PV plant and optimal sizing of the HRES.

6.1 Solar Potential Estimation Using Artificial Neural Network.

Solar Potential estimation will be done using a Machine learning technique. Accuracy of the model will be evaluated, and a most appropriate model will be proposed.

6.2 Optimal site selection

For optimal site location using GIS tool different parameters shall be considered such as distance to main road, distance to power line, solar radiation, and hydro potential. By taking into consideration different parameters GIS as decision making tool optimal site location shall be located.

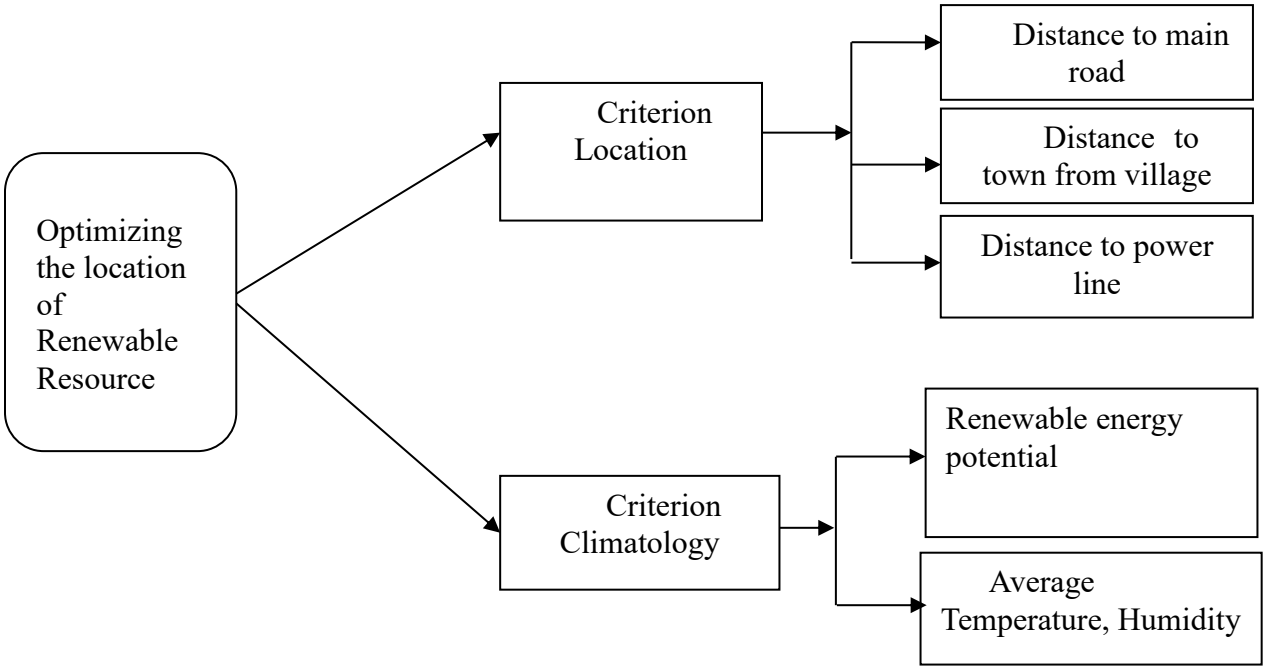

Fig. 1. Flow chart for site Selection

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